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Systems Practice in Engineering: Reflections on Teaching Research Methods and Contribution to Methodological Development¹

Dr Mike Yearworth

Systems Centre
Faculty of Engineering, Uni-
versity of Bristol, UK.

mike.yearworth@bris.ac.uk

Dr Gordon Edwards

Systems Centre
Faculty of Engineering, Uni-
versity of Bristol, UK.

gordon.edwards@bris.ac.uk

Dr Ges Rosenberg

Systems Centre
Faculty of Engineering, Uni-
versity of Bristol, UK.

ges.rosenberg@bris.ac.uk

Abstract

This paper reviews the development of research methods teaching on the Engineering Doctorate (EngD) in Systems programme at the University of Bristol. The programme is aimed at high-calibre Research Engineers working in a diversity of sectors including defence and aerospace, rail, transport, energy production, construction and the water industry. Projects concern real-world industrial problems in areas including safety, quality, sustainability and innovation: all are characterised by socio-technical complexity and require cross-disciplinary inquiry and knowledge. Current teaching is based on methods drawn from disciplines spanning systems engineering, management, problem structuring and systems thinking, and seeks to integrate methodologies from diverse research traditions. The programme fundamentally embraces the position that all hard systems are embedded in soft systems. Pedagogical developments emerge from a process of learning together: it is driven by the systemic inquiry of real-world problem situations and by the needs of industrial partners as established for each project. Results demonstrate that the programme is delivering value to industrial partners through enhanced performance, and has contributed understanding to the application of systems thinking. The generic body of knowledge being developed on this programme, though currently diffused amongst the application domains of each project, has the potential for much higher leverage. In this paper we therefore argue for a rigorous programme of research using the EngD projects themselves as the data source in order to integrate this systems thinking body of knowledge, to discover the generic issues currently inhibiting the wider implementation of systems thinking in industry, and to drive further pedagogical development. Such a programme has just been launched and will run for the next four years. This paper also makes the case that such research is best accomplished in integrative centres of excellence such as the IDC in Systems.

1. Introduction

The purpose of the research reported here is to examine and to determine how to further develop post-graduate research methods teaching on the Engineering Doctorate (EngD) in Systems programme at the University of Bristol and to discuss methodological development

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in the context of a wider research agenda focussed on systems thinking. The programme is aimed at high-calibre engineers graduating from their first degree and engineering graduates at an early or mid-career stage. Research Engineers are normally based in industry, spending about 75% of their time working in a company on innovative research for the 4-years duration of their doctorate.

The portfolio of projects is diverse: it involves more than 30 companies representing both Small and Medium-sized Enterprises (SMEs) and multinational companies; it spans industrial sectors including defence and aerospace, rail, transport, energy production, construction and the water industry; it comprises applications to product development, improvement of processes, methods and tools, and decision support; and the projects themselves seek to apply systems thinking to enhance performance and deliver better outcomes in areas such as safety, quality, sustainability, and innovation². All projects deal with problems of socio-technical complexity and use a systemic process of enquiry.

Current teaching is based on methods spanning systems engineering, management, problem structuring methods and systems thinking. Pedagogic development is itself *needs-driven*, based on feedback from Research Engineers and industrial partner organisations. In the early stages of teaching research methodology, we introduce Research Engineers to the philosophical assumptions, paradigms and strategies associated with different research traditions from physical, applied and social sciences. All are potentially relevant when researching and intervening in complex socio-technical (hard/soft) problems, and Research Engineers are challenged to develop ongoing reflective logs and action plans relating the application of these principles to the planning of their own research.

2. Method

Our method for the research presented in this paper has been to form a phenomenological description from themes arising out of the reflective logs from the Research Engineers. Causal loop modelling has been used to surface apparent sources of conflict between research and teaching. Personal reflections are used to discuss the value of the methods taught and scope for further methodological development in systems practice in engineering.

3. Development of Research Methods Teaching

The primary driver for the development of the research methods elements of the IDC Systems programme is reflected in the following requirements i) doctoral research needs methodological *rigour*, ii) Research Engineers must consider different *options* for the methodological design of their research, and iii) there must be *justification* for the research methodologies used in journal and conference publications and crucially in the doctoral thesis.

Whilst these requirements are generic and necessary for any researcher where research methods are explicitly defined and used, there is also a requirement for a definitional context for systems thinking. Although the programme is not prescriptive, there is however the need for some guidance. Two are presented here for illustrative purposes although others would be acceptable:

“Viewing situations holistically, as opposed to reductionistically, as a set of diverse interacting elements within an environment. Recognising that the relationships or interactions between elements are more important than the elements themselves in determining the behaviour of the system. Recognising a hierarchy of levels of systems and the consequent ideas of properties emer-

² Further details can be found here <http://www.bristol.ac.uk/eng-systems-centre/research/>

ging at different levels, and mutual causality both within and between levels. Accepting, especially in social systems, that people will act in accordance with differing purposes or rationalities.” (Mingers and White, 2010)

“Systems thinking is... a way of tackling complex problems. It complements scientific thinking by addressing holism, emergence and intentionality (Stakeholders and the “Human in the system”)” (Sillitto, 2009)

The research methods needed for systems research are similar to those needed for business and management research in that they i) need to deal with complex systems, ii) must allow for intervention as part of the activity of the researcher, and iii) embrace multidisciplinary approaches extending from the social sciences to traditional science. In this sense, their scope must embrace research into systems that span the areas shown in Figure 1. Also, they must ensure that the traditional (academic) research philosophy of simply *finding things out* is actively combined with the practical, managerial, imperative of defining and implementing appropriate interventions or actions for system improvement based on the findings.

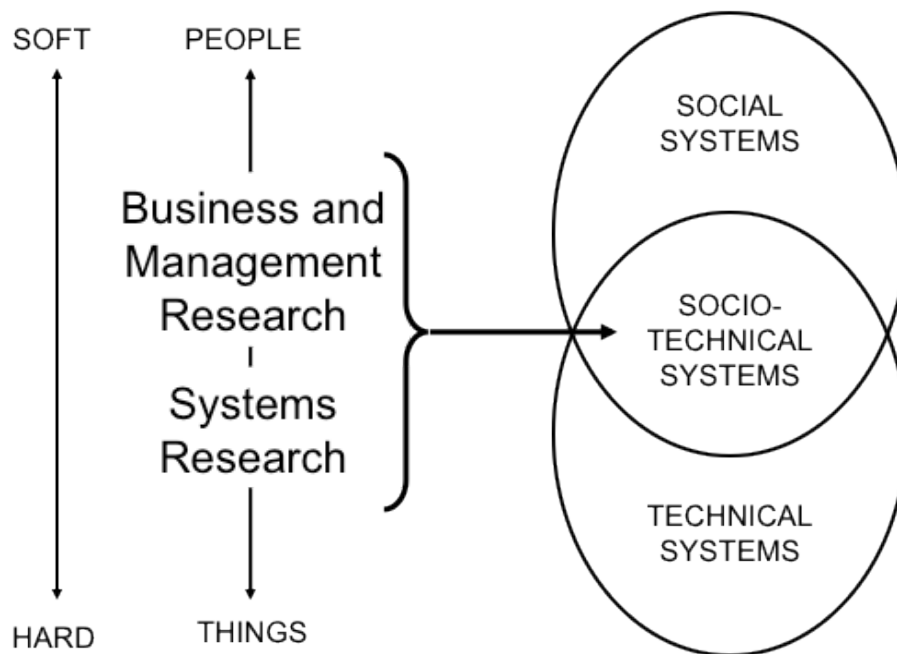


Figure 1. Research at the interface between technical (physical) and social systems

3.1. Structure of the Research Methods Teaching

Research methods teaching is structured into two blocks taught at the beginning of the first and second years of the 4-year programme.

The first component of research methods teaching provides a basis for Research Engineers to formulate their first draft methodological research plan for *their* system and problem situation. The second component of research methods follows later in the programme and feeds into a unit on advanced systems with a view to achieving methodological and intellectual rigour. This bridges the step between the basic research methods and more developed approaches needed for total systems interventions. These are based on different paradigms and are focussed around the functionalist and interpretivist socio/organisational paradigms as described by (Burrell and Morgan, 1979) and employed by (Checkland, 1999, Checkland and

Poulter, 2006) in developing his Soft Systems Methodology and by (Jackson, 2000, Jackson, 2003) in the development of his System of Systems Methodologies (SOSM) framework. This bridging step is based on current work (Edwards and Yearworth, 2011).

The remainder of the mandatory taught component of the programme covers systems engineering, mathematics for systems, technology strategy and organisation, commercialisation of new technology, and integrating engineering and management systems.

4. Analysis

Reflective logs produced as assignments by the Research Engineers in the first component of the research methods teaching have been used as a data source to assess the usefulness and effectiveness of communicating what are essentially novel research concepts for most engineers. The issues listed in the sub-sections below are selected on the basis that the Research Engineers feel that they are extremely important in their projects and that they would welcome more in-depth consideration and practice, and/or have struggled to understand and would welcome more support and input.

Philosophical Issues in Research. Research Engineers feel the need for more in-depth exposure to, and consideration of, a wide range of issues, challenges and implications arising from Checkland's view of equating the objective/positivistic philosophical position with the functionalist sociological stance, and equating the phenomenological research methods with the interpretivist (Checkland, 2006) in one *hybrid* hard/soft systems project. Also, better approaches are required for assessing the *worldviews* of stakeholders in terms of what their underlying research assumptions are (ontology – epistemology – axiology). More discussion on managing different research journeys and knowing where to categorize the complexity of their research project, e.g. with respect to the Cynefin framework (Kurtz and Snowden, 2003) together with how this may change with time and/or in different parts of the problem.

Investigation and Exploration of the Problem Field. Research Engineers would appreciate more use of, and practice in, both “*rational*” and “*creative*” initial system investigation tools, including systems/influence diagrams, rich pictures, metaphor/analogy, and communication with stakeholders using these tools. They also highlight the need for improved theory and practice in mapping and interacting with various stakeholder groups to understand different perceptions of the problem space, the drivers of complexity, the purpose of the research, and accommodating the responsibilities and aims of all stakeholders.

Problem Definition. Research Engineers question whether problem definition through structured/hierarchical research questions and hypotheses, as in traditional business and management research, is the only or best way of dealing with complex systems and wicked problems? If so, more advice on processes for generating research questions following initial system exploration, e.g. stakeholder engagement, focus groups, is seen as beneficial. If not, what alternatives exist? Also, with system understanding/perceptions among stakeholders often being in a continual state of flux - without a common understanding of the problem up front – the question of how to handle this uncertainty and when/if a problem can be frozen (for a solution to be attempted) is also seen by engineers as a problem area. This is particularly so when considered against their previous engineering research and problem solving experiences. This prompts the notion among Research Engineers of “*taming*” wicked problems (Rittel and Webber, 1973).

Research Paradigms and Strategies. Deciding among different research paradigms and strategies is recognized as a huge step by Research Engineers, with some highly contentious issues present which are countercultural and counterintuitive in engineering, and may cause problems if not handled carefully with all stakeholders. For example, justification of a pragmatic mix of positivistic and phenomenological research paradigms and strategies (often de-

manded to address real world hard/soft systems problems) can be seen as *promiscuous* and unacceptable to traditionalists from both physical and social science backgrounds. Research Engineers recognise that they must be prepared to defend such approaches in a meaningful, valid way to all stakeholders. As part of this, the question of how to address and discuss phenomenological research findings from the perspectives of rigour, validity and repeatability is seen to assume high prominence. Generally, Research Engineers feel they need more guidelines and experience in applying the more novel phenomenological research strategies - for example grounded theory (Strauss and Corbin, 1998, Fendt and Sachs, 2008), ethnography and action research – and convincing industrialists of the benefits of these approaches. As part this they recognise that, in particular, more in depth consideration of the action research strategy is required since this links strongly to wider systems intervention approaches, e.g. described in (Jackson, 2000, Jackson, 2003), and the concept of learning from trialling solutions (Rittel and Webber, 1973). Action research is also seen to raise questions around ethics, rigour, risk, and stakeholder acceptance in real-world systems situations.

Literature Review and Impact. Generally, engineers understand the need for a literature review in doctoral level work. However, they point to the fact that they generally have little experience in the application of structured approaches and tools for planning, scoping, conducting and reporting a literature review. The pros and cons of a having a dedicated literature review chapter in an EngD systems dissertation are also seen as debatable. More exposure to critical reading techniques and support on “*which aspects to be critical of*” is also highlighted.

Qualitative Data Collection and Analysis. There are a number of areas where Research Engineers feel they needed more practice and embedding of skills. These include in-depth theory, practice and language/facilitating skills for running focus groups for engineers and other stakeholders, and issues around questionnaire design and interviewing techniques. Overall, this is a contentious and highly debated subject by Research Engineers. A range of qualitative analysis techniques is considered acceptable in various areas, e.g. general business research (Saunders, Lewis and Thornhill, 2006; Gill and Johnson, 1997; Hussey and Hussey, 1997), and therefore more understanding and practice in a number of areas largely unfamiliar to engineers is considered necessary. There is a general need to improve confidence and experience of analyzing all forms of qualitative data, including use of Computer Aided Qualitative Data Analysis Software (CAQDAS) tools such as NVivo (Di Gregorio, 2003, Hutchison, Johnston and Breckon, 2009). Discourse/narrative analysis and grounded theory as techniques for analysing qualitative information (e.g. interview transcripts) to understand change and revisit theories or planned interventions are also considered important. The need to understand the meaning of unstructured qualitative data before using it to *prove* something and move onto problem solutions too quickly is also highlighted. More generally, Research Engineers also are concerned about how to convince and get support/trust from senior managers and industrialists on the rigour and merits of innovative qualitative data analysis and its combination with quantitative data: in particular, how to handle low reliability of findings – different people can get different answers from the same dataset – needs careful thought in any situation.

5. Reflections

Significantly, most Research Engineers admit to a rather superficial understanding of their “*systems*” and purposes of their project at the time of undertaking the initial research methods training. However, all express a strong desire to explore more fully their systems and problem situations as a key first step. Several indicate how the training has given them an entirely different perspective on how to make a start on their work.

Overall, Research Engineers' reflective logs indicate a very intense learning experience, which shakes them up to some extent and fundamentally challenges their existing *worldview* as engineers in relation to real world systems and systems research.

Categories emerging from the above analysis fall into two broad groups:

1. Complexity of the problem, stakeholders and system boundary, and the alignment of research questions with the industrial problem being solved, and
2. Dealing with countercultural and counterintuitive ideas from phenomenological and mixed research paradigms.

The first of these might be considered the “*bread and butter*” of systems research. The second emerging category is more problematic and can be broken down into a set of *concerns* as follows:

- a. Rigour and validity of phenomenological research approaches, e.g. the perceived weakness of induction and unreliability of qualitative data analysis;
- b. Dealing with Action Research and its links with system intervention approaches;
- c. Discomfort of having to justify phenomenology and qualitative research methods in an engineering company;
- d. Social skills necessary to conduct qualitative research and apply appropriate techniques; for example, grounded theory.

The range and scope of projects represented on the programme means that a Research Engineer might identify with any one or more than one of these categories and issues. It is the concerns about phenomenological research in an engineering context that creates the greatest supervisory load. Also, the apparent lack of integration so far in the current literature between generic research methodologies and broader systems intervention approaches provides a challenge for Research Engineers to demonstrate intellectual and methodological rigour at all levels of their work.

6. Interaction Between Research and Teaching

Systems thinking and systems practice “*continuously create each other*” (Checkland, 2010). From this we feel that it is valid to assert that systems research must be essentially practice led, which means that a university research group in systems must of necessity be connected to an industry base on which to develop its practice. In order to practice, new Research Engineers must engage in a period of teaching to gain basic skills in systems as well as the research methods that would be appropriate to studying socio-technical systems at a doctoral level. As a consequence of the practice-based nature of the EngD in Systems, it is evident that a Research Engineer is not the same as a *traditional* PhD student. The consequent structure of the research group within the Engineering Faculty is thus quite different from a *traditional* research group. This is a potential source of conflict, at least in terms of focus, and crucially, resources.

6.1. Causal Loop Modelling

In order to explore this further a causal loop model of the factors that impact the development of the systems research capability at the University of Bristol has been developed. This has been used and developed with a range of stakeholders including the Systems Centre Management Team, Systems Centre Strategic Advisory Board, Systems Research Group, a workshop of The Technical Coordination Program (TTCP), The Pro Vice Chancellor of Research, EPSRC IDC Industrial Advocates, Engineering and Physical Sciences Research Council team forming the Systems Forum, and the International Council On Systems Engineering (INCOSE).

A preliminary reflexive model, as shown in Figure 2, has been used to explore the implications of needs-driven research on the traditional academic processes that are essentially different manifestations of academic peer review:

- Routes to publication,
- Funding of research activities; especially for enlargement of research capability in specific topics through training of new researchers,
- Methods of measuring research quality which in UK Universities is through the Research Excellence Framework³ (REF), and
- Career progression within Universities.

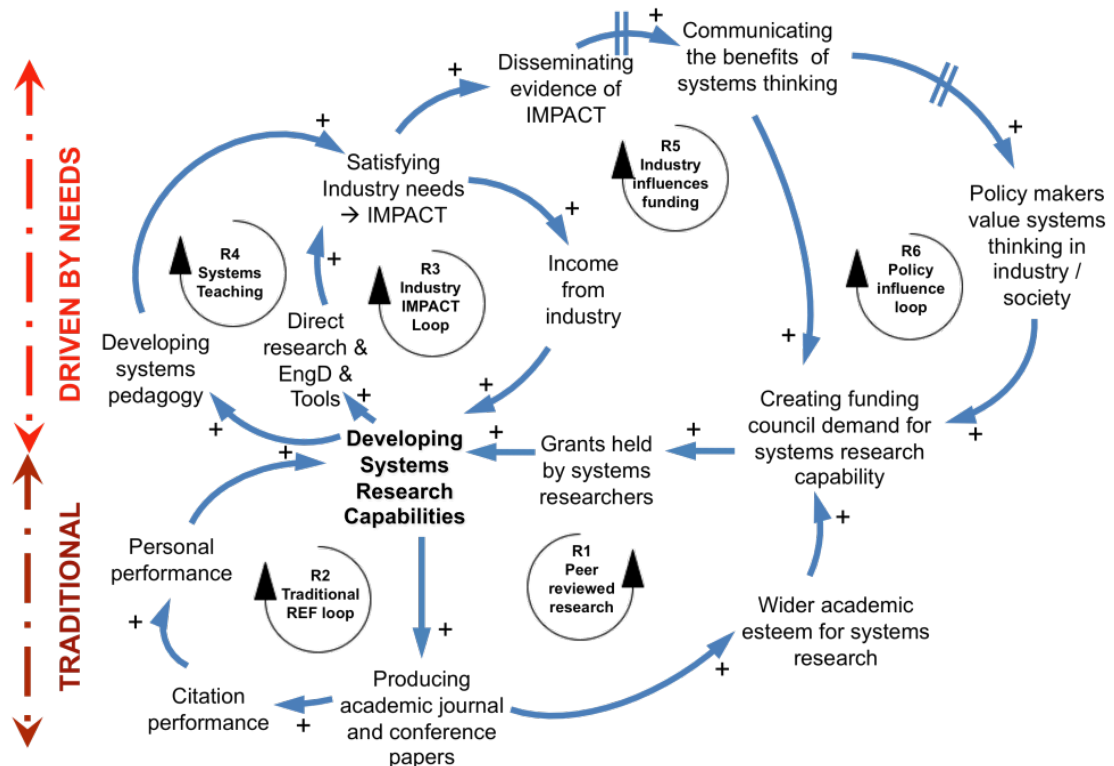


Figure 2. Causal loop model of feedback loops having an impact on developing systems research capabilities.

The reinforcing feedback loops R1 and R2 in Figure 2 represent the structural feedback forces that drive most traditional research activities in academia. Success, as assessed by such factors as citations, peer-esteem and paper performance criteria, leads to growth and further success. This is academic business as usual in the Kuhnian sense (Fuller, 2003, Kuhn, 1962) and can be viewed as the system archetype “*success to the successful*” as identified by Senge (Senge, 1990). The necessity to focus on these traditional activities can have a “*baleful influence*” on systems research (Checkland, 2006).

In contrast, the needs-driven industrial research that is the purpose of the programme explores impact in terms of:

- Developing systems thinking pedagogy – leading to greater understanding and education of researchers and practitioners (R4);
- Direct impact through the context of solving real engineering problems (R3);
- Development of the engineering toolkit for wider communication and impact.

³ Further details of this measurement system at <http://www.hefce.ac.uk/research/ref/>

To enable reliable foundations for these benefits to be accrued, a strong platform of systems engineering research principles needs to be applied. This is the gap that the IDC in Systems has been exploring. Longer-term success relies on industry and society (through government) recognising the value to the economy of systems engineering, and systems thinking generally, and voicing the demand to funding bodies, thus the reinforcing feedback loops R5 and R6. The importance of this cannot be over emphasised. The socio-technical complexity inherent in major challenges faced in projects dealing with sustainability, resilience, climate change, critical infrastructure, defence, and security, all require systemic sensibility and systems research capabilities to be developed.

7. Discussion

Whilst the results of the programme to date show that we are delivering business value to the companies involved and contributed knowledge and understanding to the application of systems thinking to a wide range of problems, it has not as yet focused on the contributions it could make to the general body of theoretical knowledge that is known as systems thinking. Preliminary data suggest that we have yet to achieve a coherent and well-theorised synthesis from across the programme. The situation has parallels with that faced by Peter Checkland and his colleagues in the 1970s (Checkland and Jenkins, 1974) that led to the development and wide application of the Soft Systems Methodology (Checkland, 1999, Checkland, 2010).

The programme fundamentally embraces the position that all hard systems are embedded in soft systems and they cannot be treated independently, and through various framing methods (Jackson, 1993, Jackson, 2001, Kurtz and Snowden, 2003, Midgley, 2003, Rittel and Webber, 1973) the Research Engineers use a variety of systems approaches, methodologies, strategies, methods and tools for their research projects. We recognise implicitly that the programme is one of Action Research, in that our systems thinking is evolving in response to knowledge gained from the application of systems thinking on the programme, and that this in turn impacts beneficially on our shared systems pedagogy and practice. Until now this has not been made explicit with an associated methodological design that encompasses facets of the entire programme (methodology – pedagogy – practice).

Systems research for industry is generally application or domain specific, whereas the body of knowledge that is systems thinking is an abstraction which itself is independent of application domain. Research Engineers on the programme learn about systems thinking largely by doing, i.e. applying selected material and tools from the taught units to their actual real world problem situations. The pedagogy of systems thinking emerges from the process of learning together on the programme; it is enquiry driven. However, generic research that feeds into this body of knowledge, which has the potential for much higher leverage, tends to get diffused into the application domains. This is a problem for all crosscutting processes; that is why they need to be concentrated in integrative centres of excellence such as the IDC in Systems. These centres have to avoid becoming transactional, domain specific, silos themselves and we therefore see a strong need to improve systems research processes in engineering and the physical sciences, a position supported by evidence from other researchers in specific areas – rigour (Brown, 2009), discipline development (Brown, 2009, Ferris, Cook and Honour, 2005), pedagogy (Valerdi and Davidz, 2009), and stronger industry-academic collaboration (Henshaw, Gunton and Urwin, 2009).

To meet this need we see there is an imperative to conduct a rigorous programme of research using the EngD projects themselves as the data source in order to discover the generic issues currently inhibiting the wider implementation of systems thinking in industry. Such a project has just been launched and will run for the next four years.

8. Biographies

Dr Mike Yearworth is a Reader in Systems at the University of Bristol where he is responsible for developing research strategy and is course director for Advanced Systems and Research Methods teaching. His research is focused on the development and application of systems based methods for working with complex socio-technical problems. Prior to joining the University he was Senior Research Manager at Hewlett-Packard's European Research Laboratory and previously Director of the Intelligent Computer Systems Centre at the University of the West of England. He is a Chartered Engineer and holds an MBA from the University of Bath and BSc and PhD degrees in Physics from the University of Southampton.

Dr Gordon Edwards is a Visiting Fellow in Systems at the University of Bristol. He has been involved in teaching research methods for business, management and systems at the University since the mid 1990's. Most recently his work has focussed on research and intervention strategies for problem situations in complex socio-technical engineering systems. Previously, Gordon was Head of Engineering Research in Shell International. During a 20 year Shell career, he also held various line management and staff consultancy roles in Shell companies in Europe, the USA and the Far East. Gordon holds BSc and PhD degrees from the University of Nottingham and is a Fellow of the Institution of Mechanical Engineers

Dr Ges Rosenberg is Systems Research Development Manager and a Visiting Fellow at the University of Bristol, with responsibility for developing industrial partnerships. His background includes experience in mathematical simulation and modelling for aircraft structures, their dynamics and control. He received his PhD from the University of Bristol in 2003, after completing a dissertation on "Systems-based Approaches for Managing Environmental Risk". He became Operations Director at Stirling Dynamics from 2003 until June 2010, and is a Member of the Institute of Directors and the Chartered Institute of Quality Assurance.

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